

RESPONSE OF NON-SEISMIC RC FRAMES TO HIGH-SPEED EXCITATIONS

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ABSTRACT

This paper presents cyclic test results of reinforced concrete (RC) connections that are not designed to withstand seismic actions. Three full-scale RC beam-column sub-assemblies are tested under an axial compression and displacement cycles at varying speeds. The results reveal that joint panels of non-seismic RC connections are weaker than the adjoining members, and cyclic loading of such connections induces significant joint shear deformation that eventually leads to failure. The overall resistance of non-seismic frames is hence proportional to the shear capacity of its joints. The test results also show that with an increase in loading speed, non-seismic RC connections can withstand a larger load and drift, and undergo a smaller joint shear deformation.

INTRODUCTION

In low or moderate seismicity regions, RC building frames are designed to resist dead and live loads only. Consequently, it results in seismically inadequate reinforcement details inside the joints, which make such frames vulnerable to joint shear failure when subjected to ground excitations [Beres et al. 1992; Hakuto et al. 2000]. Although earthquakes of significant magnitude are unlikely to occur, non-seismic building frames may yet be subjected to ground shocks resulting from construction and explosion in the vicinity. Such ground shocks consist of significant high-frequency components, which force the building frames to respond in higher order modes characterized by high-frequency and small-amplitude vibrations [Dhakal and Pan 2003a]. Hence, a thorough understanding of the response of non-seismic frame components to high-speed cyclic excitations is needed. In this study, behaviors of non-seismic RC beam-column sub-assemblies subjected to cyclic loadings at various speeds are investigated experimentally.

EXPERIMENTAL PROGRAM

The tests described in this paper are a part of an experimental research project on damage assessment of lightly reinforced concrete beam-column joints under reversed cyclic loading [Pan et al. 2001], which was a collaboration between the Protective Technology Research Centre (PTRC), Singapore and the National Center for Research on Earthquake Engineering (NCREE), Taiwan. The specimens used in the three tests were identical. The geometrical dimensions and cross-section details of the specimens are shown in Fig. 1. Note that the column main bars and the beam bars at the bottom are discontinuous and are overlapped just adjacent to the joint, and no vertical or lateral hoops exist inside the joint core; features that are typical of non-seismic frames [Beres et al. 1992].

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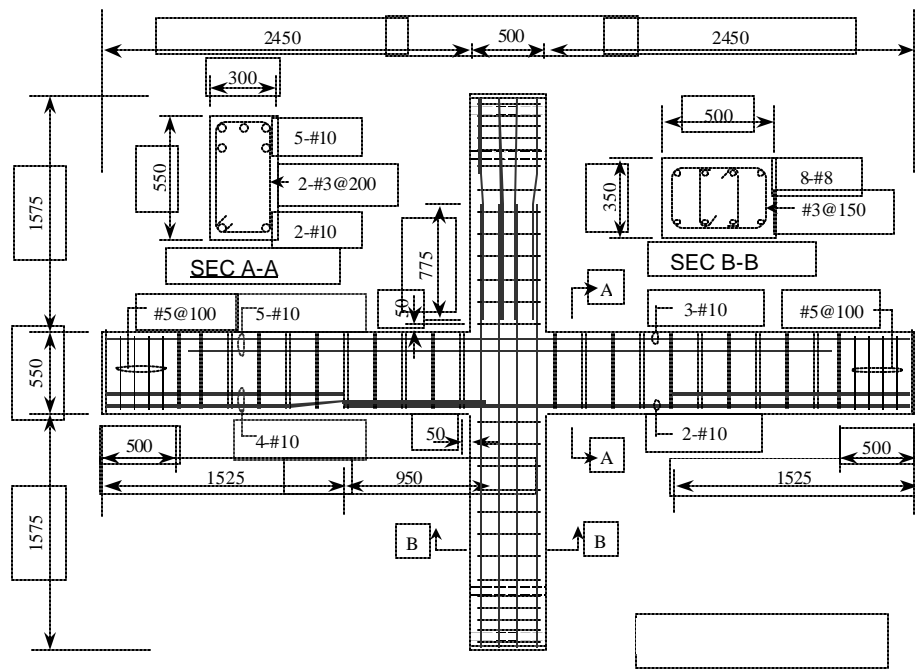


Figure 1 Geometrical features and reinforcement details of the specimens

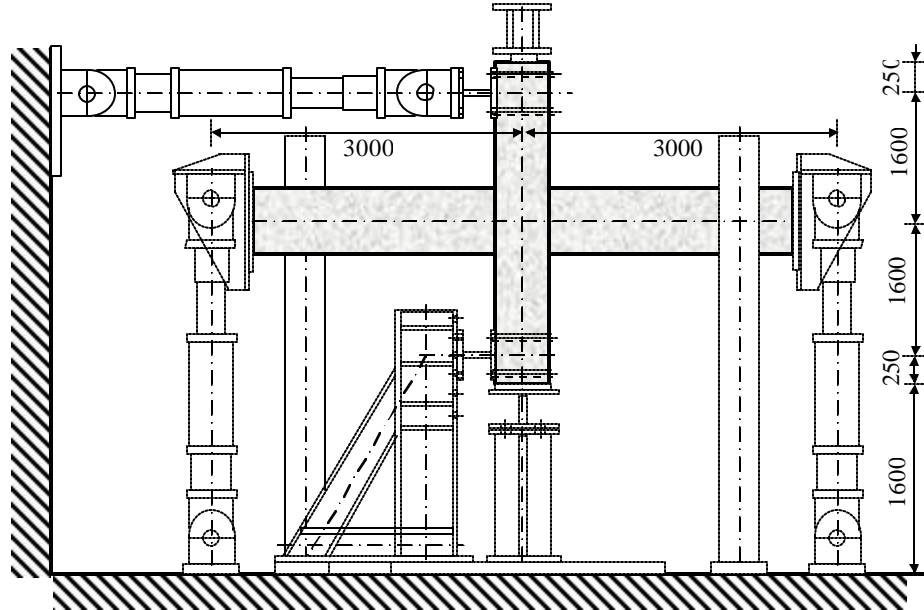


Figure 2 Test set-up

The test set-up is schematically illustrated in Fig. 2. Owing to the connection details, the effective height and length of the specimen were 3.2 m and 6.0 m respectively, which are different from the original specimen dimensions. A steel H beam was placed on the column top and was clamped with the strong floor through two prestressing tendons used to apply an axial compression. The axial compressive force was monitored using two external load cells connected to the prestressed tendons. Reversed cyclic displacements with gradually increasing amplitude were applied at the beam tips. The displacements and the forces at the beam tips and the column top were obtained from the load cells and LVDTs integrated in the corresponding actuators. Shear deformation of the joint panel was also measured with a pair of pi-gauges attached diagonally on the joint surface. In addition, strain gauges were also used to monitor the strain of the main bars and the stirrups near the joint core. Precaution was taken in selecting and using the loading devices, response-measuring gauges and data-recording instruments; especially for the high-speed tests [Dhakal and Pan 2003b].

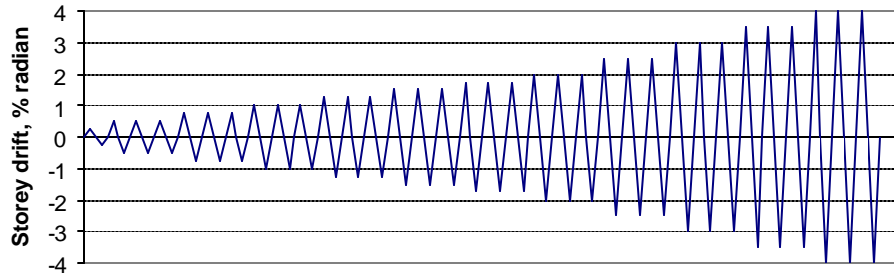


Figure 3 Cyclic loading history followed in the PD and ND tests

Due to symmetrical nature of the specimens, the displacements applied at the two beam tips at any instant were equal in amount but opposite in direction. A complete sequence of story drift applied in the first test denoted as PD (pseudo-dynamic) is depicted in Fig. 3. Here, story drift is the angle made by the line joining the beam tips with the original beam axis and is equal to the summation of the displacements applied at the two beam tips divided by the effective beam length. The amplitude of the story drift cycle was increased gradually from 0.25% to 2% with a 0.25% step-wise increment and was increased thereafter with a 0.5% step-wise increment until failure. The first cycle corresponding to 0.25% story drift was applied once only, and each cycle thereafter was repeated thrice. In the second test identified as ND (normal-dynamic), the same displacement sequence was applied at a constant frequency of 2 Hz. In the third test identified as HD (high-dynamic), 30 additional cycles of smaller amplitude were applied before the sequence shown in Fig. 3 began, and the displacement cycles were applied at the maximum possible frequencies. Consequently, the gradual increase in amplitude was accompanied by a gradual reduction in cyclic frequency, starting from 20 Hz for the smallest (± 2 mm) cycles and gradually reducing to 2 Hz for the largest amplitude (± 120 mm) cycles.

TEST RESULTS

Damage observation

Although cracks were checked regularly in the PD test, displacement cycles were not interrupted in the ND test until the 2.5% story drift cycles had been applied. Whereas in

the HD test, the loading was paused after each step until the first crack could be noticed. Thereafter, the loading was stopped only after completing the 2.5% story drift cycles. In the ND and HD tests, the completion of the 2.5% story drift cycles was selected for damage inspection because the specimen during the PD test showed the first sign of failure at this instant. It was also because a story drift of 2.0 to 2.5% is thought to be a representative value to gauge RC beam-column joint's seismic performance [Otani et al. 1985]. In both ND and HD tests, the loading was stopped after each step corresponding to a story drift larger than 2.5% in order to assess the damage and decide whether the loading should be continued.

Diagonal cracks appeared on the joint panel surface before any cracks could be seen in the adjoining members. In the PD test, cracks appeared on the joint during the 0.25% radian story drift cycle whereas in the HD test, diagonal cracks were visible only after completing the 0.75% story drift cycles. As the loadings were continuous until 2.5% story drift, the crack initiation in the ND test and crack propagation in the ND and HD tests could not be monitored. The damage on the specimens after completing the 2.5% story drift cycles is illustrated in the photographs in Fig. 4. After the 2.5% story drift cycles, specimens in the ND and HD tests incurred apparently less damage than that in the PD test did. When the tests were terminated, damage was mostly concentrated in the joint panel, and the beams and the columns had only a few cracks. As expected, the reinforcing bars inside the beam and column did not yield.

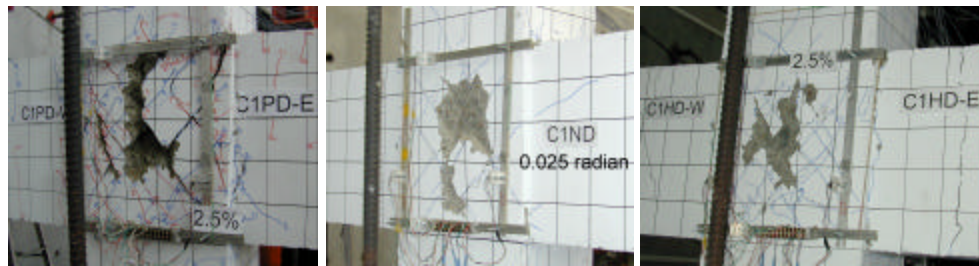


Figure 4 Specimens after 2.5% story drift cycles

Cyclic responses of the specimens

As the specimens were symmetric and equal and opposite displacements were applied at the beam tips, the load-displacement relationships at the two loading points were identical. The cyclic load versus displacement curves at one of the beam tips for the three tests are shown in Fig. 5a. The maximum actuator force recorded in all tests in the two opposite directions are not equal due primarily to the different amounts of reinforcement at the top and bottom of the beam. Interestingly, the curves in the ND and HD tests are found to suddenly unload at the peaks of each cycle. The extent of unloading in the ND test becomes more prominent during the larger drift cycles, whereas it is prominent even during the smaller drift cycles in the HD test. A scrutiny of the results revealed that this behavior is mainly attributable to the development of a large acceleration and thus an inertial force generated in the direction opposite to that of the displacement being applied. This mechanism, which is unusual in quasi-static cyclic loading tests, is discussed in more detail elsewhere [Dhakal and Pan 2003b].

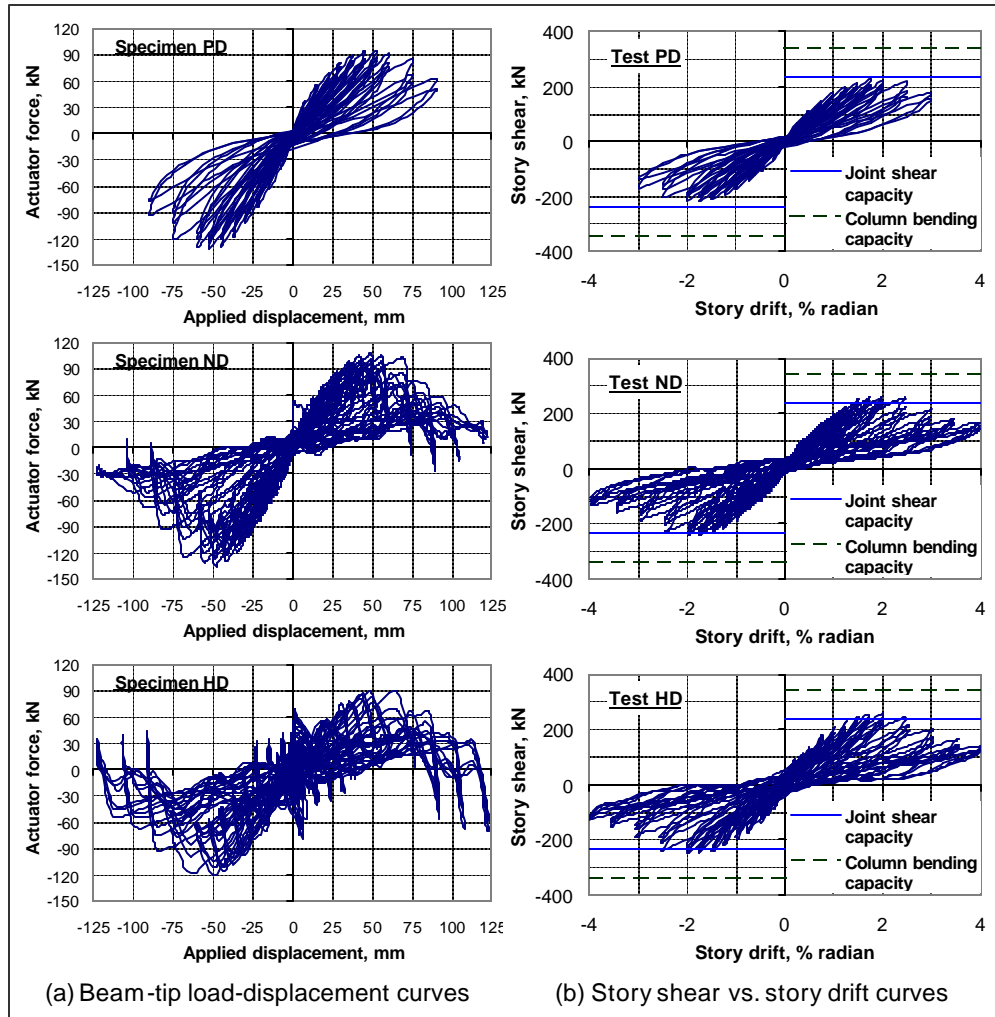


Figure 5 Cyclic responses of the three specimens

Fig. 5b shows the relationships between the story shear force and the story drift for the three tests. Here, story shear force is the horizontal reaction force measured by the actuator at the column top. Interestingly, the story shear force versus story drift plots did not show the unloading dips at the peak of each cycle. Note that the column top was restrained against lateral movement, thereby avoiding the development of any acceleration and inertial force there. Hence, the force measured directly at the column top represented the correct story shear force. It would not be possible to retrieve the correct story shear force, if it was derived from the forces measured at the two loading actuators or if the cyclic displacement was applied at the column top instead of at the beam tips.

As the story shear force is in equilibrium with the forces at the two loading points, the maximum story shear forces in the two opposite directions are equal, despite different amounts of reinforcing bars at the top and the bottom of the beam. The cyclic loops pinched severely absorbing a small energy. Moreover, the hysteresis curves did not show any yielding plateau as the reinforcing bars remained elastic throughout the tests, and the response was brittle with the story shear force starting to soften immediately after attaining its peak value in all three tests. The story shear force corresponding to the allowable joint shear stress recommended by the ACI 352-91 [1991] and that corresponding to the flexural capacity of the column computed using the measured material strengths are also indicated in the plots. Note that the peak story shear force is much less than the story shear force corresponding to the column flexural capacity but is close to that corresponding to the joint shear capacity. These observations hint that the overall response of these specimens was governed by the joint, and no plastic hinge was formed in the adjoining members, which was further verified by the strain gauge readings.

In the PD test, loading was terminated after the story shear force degraded by more than 20% in three cycles. In contrast, failure point could not be precisely determined based on this criterion in the ND and HD tests as the shear force degradation in three cycles varied randomly showing no correlation with the applied story drift, and the high-speed tests were hence terminated after the specimens were visibly damaged severely. Thus, the ND and HD tests could be continued until the story drift reached 4.0% whereas the specimens in the PD tests failed at 3.0% story drift. Interestingly, the maximum story shear force observed in the tests were not noticeably less than that corresponding to the code-recommended allowable joint shear stress despite the lack of transverse hoops inside the joints, thereby corroborating that the code recommendations may have been expectedly conservative. As the results show, increase in the loading speed enhanced the maximum capacity, albeit not drastically.

Joint panel response

Overall drift of beam-column sub-assemblies originates from two major sources, namely member deformation that comprises flexural and shear deformations of the beam and column, and the joint panel shear deformation. As the damage was mainly concentrated on the joint and the specimens experienced joint shear failure, the major share of the applied story drift must have been consumed by the joint panel shear deformation. For validation, the joint panel shear deformations measured in the three tests are plotted against the applied story drift in Fig. 6. Two dashed straight lines corresponding to 15% and 50% of the applied story drift are also drawn in the figure. As the pi-gauge readings were disturbed after the spalling of concrete from the joint surface, shear deformation of the joint panels could not be computed for story drifts larger than 2.5%.

As can be observed, the joint shear deformation in all specimens account for more than 15% of the applied story drift and its contribution kept on increasing as the loading progressed. Note that 15% may be taken as an upper-bound representative value of the contribution of joint shear deformation to the story drift in seismically designed ductile frames. The contribution reached as high as 50% in the PD and HD tests. Comparing the PD and ND test results, it can be said that an increase in the loading speed substantially confines the joint panel shear deformation. The joint deformation in the HD test was larger than that in the ND test in spite of the higher loading speed. This must be due to the additional thirty displacement cycles applied in the HD test.

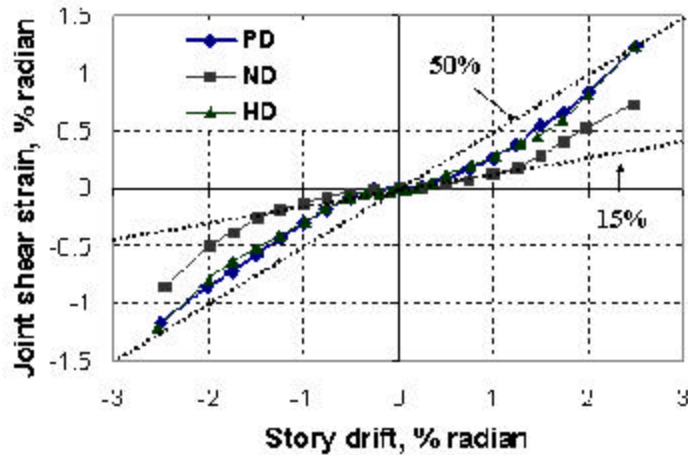


Figure 6 Comparison of joint shear contributions to the story drift in the three tests

CONCLUSIONS

Cyclic loading tests were conducted on three full-scale RC beam-column sub-assemblies that were designed only for the gravity loads. The test results implied that non-seismic RC frames experience severe damage in the joint panel when subjected to lateral load reversals. Consequently, joint panels of such frames experience significant shear deformation which should be given due consideration in analyzing such frames. The strength and deformability of the non-seismic joints tested were not apparently inferior. Notwithstanding the lack of hoops inside the joints, the tested specimens could endure joint shear stress at levels commonly expected of seismically designed ductile joints. The comparison of the test results led to a conclusion that an increase in the cyclic loading speed increases the capacity and deformability of non-seismic frames, and also restricts the shear deformation of the joint panel, thereby making the non-seismic frames less vulnerable to excessive joint damage.

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